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# A multi-criteria group decision-making method for the thermal renovation of masonry buildings: the case of Algeria

**Abstract**

The future of masonry buildings with heritage values is certain – the investments in making such buildings energy-efficient during renovations to meet the energy consumption requirements will increase over the next decade. However, decision makers fail to address the concerns of each project actor and give specific answers on how basic requirements on such historical buildings can be implemented. This paper proposes a new multi-criteria group decision-making method for the thermal renovation of masonry buildings. The aim of the proposed method is to rank different renovation solutions. The method uses; the structured group interaction method Delphi to define the evaluation criteria and the thermal renovations solutions, Swing method to facilitate the process of the determination of the criteria weights, the group decision support system (PROMETHEE GDSS) to reach a global ranking of the renovations solutions, PROMETHEEV to introduce additional constraints, as well as the Graphical Analysis for Interactive Aid (GAIA) analysis to get a better understanding of conflicts and similarities between the criteria and among the decision makers. We proceed to exemplify by means of a real-life case project in Algeria and offer suggestions on what front-ended stakeholders could do to reduce the energy consumption in masonry buildings.

Keywords: thermal renovation, masonry buildings, PROMETHEE methods, multi-criteria decision-making, group decision.

## 1 Introduction

Residential and tertiary sectors in Algeria consume about 34%of the total energy production in the country. The government has launched in 2016 a thermal renovation program for existing buildings to reduce the energy consumption. This program is led by the national agency for the promotion and the rationalization of the energy use (APRUE). It aims to insulate 100.000 houses per year. The national fund for energy management (FNME) will provide 80percent of the costs related to these interventions [1].The existing building stock in Algeria has reached 6,500,000dwellings in 2016, from those 1,050,000 consist of masonry dwellings built before 1945. The majority of masonry buildings were built during the French colonial period. These buildings rep-resent a valuable architectural heritage. They were constructed using traditional techniques and materials (for e.g. load bearing walls of stone masonry, vaulted brick floor and metal beams) [2].The masonry buildings are subject in Algeria to a wide preservation program, many buildings rehabilitations are undertaken across the country. In 2016, the government envisages the diagnostics of 300.000 dwellings. Rehabilitation operations will be launched following these diagnostics. These actions will be conducted and financed by the government. The buildings rehabilitation will concern only common parts of buildings (exterior facades, yards, cellars, entrance halls, stairwells, accessible and inaccessible terraces, and pitched roofs) [3].The energy-saving program in the residential sector and the rehabilitation of masonry buildings program offer a great opportunity to perform the thermal renovation of masonry buildings. This will balance between the improvement of the thermal performance of the existing buildings stock and the perseveration of masonry buildings. However, the choice of improvement alternatives during their thermal renovation is a complex decision because:

- It involves different stakeholders (actor concerned with the preservation of buildings, actor concerned by the reduction of energy consumption, building users, and so on) that can express a multitude of criteria (economic, energy, cultural, historical, and so on).
- The communication among the actors to obtain a consensus regarding the definition of evaluation criteria, and the potential thermal renovation solutions might be complicated due the differences in their respective backgrounds.
- The difficulty in assessing the importance of each criterion for each actor.

Due to the multi-decision makers and multi-criteria character of the thermal renovation of masonry buildings in Algeria, it is difficult to find solutions that can optimize all the criteria at once. Therefore, it would be more appropriate to find consensus solutions. The multiple-criteria decision analysis is a useful tool for this type of problem; it evaluates different solutions taking into account both the preferences of decision makers and the different criteria. Many research studied the application of multi-criteria decision methods in the renovation of masonry buildings [4–7].Yet, only few works focused on the use of such methods in order to make masonry buildings energy-efficient [8–10]. This paper pro-poses a new group decision aid method that combines the Delphi method, the Swing method, and the Preference Ranking Organization Method for Enrichment Evaluation PROMETHEE methods [11] for the thermal renovation of masonry buildings with a heritage value. The aim of the proposed method is to rank different thermal renovation solutions using a multi-criteria and multi-decision makers approach. This paper is divided into six-parts, the following section presents a literature review concerning the application of multi-criteria decision aid methods in the field of thermal renovation, part 3 develops the method used in this paper, part 4 provides the results of the application of the method on a case study, Section 5 evaluates the proposed method, while Section 6 presents conclusions and directions for future research.

## 2 Literature review

Different methods were applied to support decisions for the thermal renovation of buildings [8–10,12,13–26]. These methodologies can be categorized into two main families as indicated in Zavadskas et al. [12]: the Multi-Criteria Decision Aid methods (MCDA), in which the numbers of alternatives to consider is finite and known, and the Multi-Objective Optimization methods (MOO),which enables the consideration of an infinite set of alternatives.

### 2.1 Multi-criteria decision aid (MCDA) methods

MCDA used for the thermal renovation of buildings can be ranked into two different approaches, the partial aggregation approach, and the complete aggregations approach.

#### 2.1.1 The partial aggregation approaches

The advantage of this approach is that it provides the opportunity to take into account both quantitative and qualitative criteria without having to do any coding. It does not allow compensation between criteria such as facing two actions "*a*" and "*b*" it is based on the assumption that "*a*" outrank "*b*", if "*a*"  is at least as good as "*b*" on a majority of criteria without being too much worse in other criteria. Rey [13] proposed an outranking MCDA with partial aggregation from the ELECTRE (ELimination and Choice Expressing the REality) methods for the thermal renovation of office buildings. Outranking methods were also applied to study air conditioning systems [14]. Catalina et al. [15] applied MCDA method ELECTRE in order to select an appropriate multi-source energy system for residential houses. Avgelis and Papadopoulos [16] used ELECTRE in order to rank different HVAC systems in a university building regarding energy costs and inflation, as well as the economic and life cycle costs of acquiring a system.

#### 2.1.2 The complete aggregation approach

The complete aggregation approach gives a note to all scenarios, whilst basing the score on the most important criteria. However, this approach presents several limitations. It allows the compensation of low score in criteria with good results on several other criteria. Also, it is necessary to carry out a coding while taking into account both quantitative and qualitative criteria. Roulet et al. [17] suggested a multi-criteria rating methodology based on a complete aggregation approach in order to assess the effectiveness of various thermal renovation scenarios.

Blondeau et al. [18] tested MAUT (Multi-Attribute Utility Theory) technic in the study of summer ventilation strategies in an educational building. Their findings highlighted the limitations of this method. It is completely compensatory and it sometimes provides counter-intuitive results. Alanne [19] applied a multi-criteria decision aid model type “knapsack” to help designers to choose the most appropriate renovation actions during the design phase of a project. The advantage of this model is to treat a portfolio optimization case by introducing constraints. The disadvantage is the purely additive character of the model.

Medineckiene and Björk [20] applied the multi-criteria decision aid method SAW (Simple Additive Weighting), MEW (Multiplicative Exponential Weighting), and COPRAS (COmplex PRoportion ASsessment) to choose solutions for the thermal renovation of Swedish residential apartments. Kontu et al. [21] proposed the multi-criteria decision aid method SMAA (Stochastic Multicriteria Acceptability Analysis) to assess which heating system would be best for new single-family homes. The advantage of both approaches cited in this paragraph is to take into account the preferences of the building users, they were involved in the decision process using interviews for the first method and questionnaire for the second in order to get their preferences regarding different evaluations criteria.

Šiožinytė et al. [22] applied the TOPSIS Grey (Technique for Order Preference by Similarity to Ideal Solution with grey numbers) and AHP (Analytic Hierarchy Process) methods to find the best compromise solution in order to make vernacular buildings energy efficient. Different criteria were considered, such as architectural heritage, requirements (norms), energy and comfort. Ruzgys et al. [23] applied an integrated SWARA (Step-wise Weight Assessment Ratio Analysis) –TODIM (an acronym in Portuguese of Interactive and Multi-criteria decision-making) multi-criteria decision-making method in order to rank the best alternatives of residential building modernization in Lithuania.

Terracciano et al. [9] have studied the analysis of vertical addition systems for energetic retrofitting of existing masonry buildings. The multicriteria decision-making TOPSIS method have been used in order to compare the vertical addition systems with each other in terms of structural, environmental and economic performance parameters. Zagorskas et al. [10] applied TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method to select the best insulation option for historic buildings among five internal insulation materials. This method takes into account five criteria: cost of the material, complexity of the installation, heat transfer coefficient, loss of space, and moisture properties of the material. The relevance of both methods presented by Terracciano et al. [9], and Zagorskas et al. [10] compared to all the other methods cited previously, is that they take into account the specificity of the thermal renovation of masonry buildings with a heritage value. However, they both have several limitations, such as the method proposed by Zagorskas et al. [10] can be applied only for the internal insulation of buildings, while the method suggested by Terracciano et al. [9] can be used only for the selection of vertical addition systems. In addition, both methods do not take into account the preferences of different decision makers, and they are completely compensatory.

### 2.2 Multi objective optimization (MOO) methods

All the previous MCDA methods cited in subsection 2.1 assume that the number of action to evaluate is finite. Multi objective optimization methods are relevant as they enable the user to consider an infinite set of alternatives. Diakaki et al. [24] applied an MOO method to improve energy efficiency in buildings. It allows considering an infinite number of actions and evaluating them through various criteria. The evaluation criteria include the annual primary energy consumption of the building, annual emissions of carbon dioxide and the initial cost investment. Asadi et al. [25] proposed an MOO method to help stakeholders in the definition of intervention measures. The method aims to minimize the use of energy in the building profitably while satisfying the needs of the occupant. Asadi et al. [26] suggested an MOO method using genetic algorithm capable of evaluating different scenarios in a renovation project. Different criteria were considered including the energy consumption, the cost of the renovation, and the comfort of the occupant. Brauers et al. [8] have presented the application of the MOO method MOORA (Multi-Objective Optimisation by Ratio analysis) and MULTIMOORA (MOORA plus Full Multiplicative Form) with discrete  dimensionless measures in order to find an optimal solutions for the thermal renovation of masonry buildings from the Soviet period.

Contrary to multi-criteria decision aid methods, Most of multi objective optimization methods do not allow the ranking or the selection of the best solutions. They only allow the identification of a set of effective solutions and the description of accessible compromises. Furthermore, the complexity of the MOO methods makes their use difficult. In order to achieve the objective of the study presented in this paper, the use of multi-criteria decision aid methods is considered more appropriate as they allow a complete ranking of the thermal renovation solutions.

MCDA and MOO methods were often used in the literature for the thermal renovation of buildings. However, they were rarely applied for the thermal renovation of masonry buildings with a heritage value. So far, none of the current methods takes into account at the same times the following aspects:

- The specificity of the thermal renovation of masonry buildings with a heritage value.
- A multitude of criteria and thermal renovation solutions, expressed by several decision makers to get a global ranking of the actions.
- The communication among the decision makers to obtain a consensus regarding the definition of evaluation criteria, and the potential thermal renovation solutions.

- The difficulty in assessing the weights (importance) of each criterion for each decision maker.
- Additional constraints such as the maximum budget allocated to the operation.
- Conflicts and similarities between the criteria and among decision makers for a better understanding of the decision problem.
- The application of the partial aggregation MCDA methods PROMETHEE.

The current paper proposes a new group decision aid method that combines the Delphi method, the Swing method, and the PROMETHEE methods for the thermal renovation of masonry buildings with a heritage value.

### 2.3 PROMETHEE methods

PROMETHEE methods are outranking methods that use the partial aggregation. They are useful in the case where the number of alternative to rank is finite. These approaches compare the actions pairwise, and under certain conditions check if one of two actions clearly outrank the other or not from these comparisons. They allow a comprehensive ranking of the various alternatives [27]. PROMETHEE methods include PROMETHEE II, the GAIA analysis (Graphical Analysis for Interactive Aid), PROMETHEE V (Optimization under constraints), the group decision support system PROMETHEE GDSS, and other extensions.

#### 2.3.1 PROMETHEE II

PROMETHEE II assumes that the decision maker is able to give a weight and a preference function to each criterion. This information is used to compare the actions in order to establish a comprehensive ranking. Furthermore, the GAIA analysis which is a graphical representation of the problem allows a better understanding of conflicts and similarities between the criteria and the performance of each action regarding different criteria [27], this whole process is explained in the methodology section. Macharis et al. [28] provided a comprehensive literature review on the application of the PROMETHEE II method in various areas. It has been used for the environmental management [29-33], hydrology and Water management [34, 35], and energy management [36-39].

### 2.3.2 PROMETHEE V

PROMETHEE V allows adding additional constraints required by the decision maker, such as the number of alternatives to be selected, the maximum budget allocated to the operation, and incompatibilities between actions. It also argued that many other types of constraints can be added [40]. This method has already been used by Vetschera and de Almeida [41] to solve a portfolio optimization problem. Fontana and Morais [42] used PROMETHEE V to assist decision makers in selecting a set of feasible alternatives for rehabilitating the greatest number of leakage points in a water network.

### 2.3.3 PROMETHEE GDSS

PROMETHEE GDSS takes into account the preferences of a group decision. First, the decision makers identify different alternatives and different criteria. Then an individual ranking is established for each decision maker through PROMETHEE II. Furthermore, the method brings together the different individual rankings for a global ranking. This ranking takes the preferences of all decision makers into account. Finally, the global GAIA analysis identifies the decision makers that share similar preferences and those in conflict [43].

PROMETHEE GDSS has been successfully implemented to solve multi-criteria and multi-decision maker problems in various areas. Tavana et al. [44] applied it for the oil and gas pipeline planning in the Caspian Sea. Behzadian et al. [45] applied PROMETHEE GDSS to rank technical requirement alternatives in line with customer needs during the final stage of the house of quality process. Gonçalves and Belderrain [46] investigated the application of PROMETHEE GDSS and GAIA methods for the performance evaluation in the subsystems of the ITA-SAT satellite project.

Turcksin et al. [47] used the combination of the AHP and the PROMETHEE GDSS methods in order to select the most appropriate policy scenario to stimulate a clean vehicle fleet.

The advantage of PROMETHEE methods is that they use the partial aggregation. These methods allow taking into account several quantitative and qualitative criteria without having to do any coding or change the indicators. They do not allow compensation between criteria. With PROMETHEE GDSS, it is possible to reach a global ranking of the actions taking into account the preferences of several decision makers. PROMETHEE V allows considering additional constraints. Finally, GAIA analysis provides information on conflicts and similarities between the different criteria and among the decision makers. However, PROMETHEE methods do not provide any specific guidelines to facilitate:

- The communication among the actors to obtain a consensus regarding the definition of evaluation criteria, and the potential thermal renovation solutions.
- The assessment of the weights (importance) of the criteria.

## 3 Methodology

This section presents a new group decision aid method that combines the Delphi method, the Swing method, and the PROMETHEE methods to evaluate different renovation solutions. The method consists of several sequential steps as presented in Figure1: first, the group of decision makers is constituted. After that, the building is investigated, then after through Delphi method the criteria and the thermal renovation solutions are defined. Later with Swing method, each decision maker provides information between the criteria expressed by weights. Finally, the rest of the calculations will be completed using PROMETHEE methods. More details concerning the different steps would be presented in the following subsections.

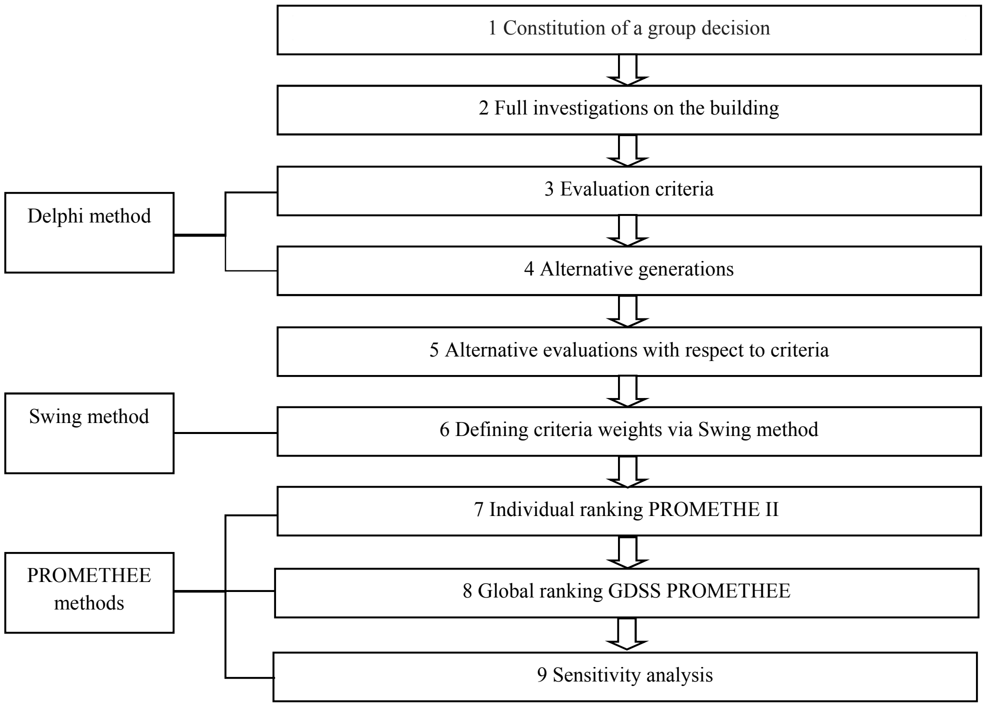



Figure 1: Proposed methodology to rank different thermal renovation solutions

### 3.1 Constitution of a group decision

The first step is to form a group consisting of the different decision makers involved in the thermal renovation project (actor concerned with the preservation of buildings, actor concerned by the reduction of energy consumption, owners, and so on).

### 3.2 Full investigation on the building

Following the constitution of the decision makers group, a complete documentation of the building would be performed. This step combines a pre-evaluation of building design plans and documentation as well as the level 1 audit (walk-through assessment) as demonstrated in Alajmi [48]. Based on the information collected during the investigation on the building step, each decision maker can have an idea concerning the potential evaluation criteria and thermal renovation solutions as argue by Ma et al. [49]. First, in order to familiarise the decision makers with the building in investigation a pre-evaluation of the building plans and documentation, without any visit to the site should be performed. The data collection concerns the following aspect:

- The implantation of the building and the climate zone.
- The internal organization (plans, sections).
- The plan of facades with full details.
- The area and volume of the building.
- The methods of construction of the building and the openings (load bearing elements, walls, nature of the connections, roof, flours, and windows type).
- The energy consumption and the technical equipment's.

Later, the group decision should carried out a walk-through assessment, which is the simplest type of audit and the most basic requirement of the energy audit [50]. This level of audit may takes several visits to the building by the group decision makers. The walk-through assessment allows a real evaluation of the current situation of the building, its technical equipment's, and the energy performance of the building. Furthermore, an interview with the building's users would provide a better understanding concerning the building exploitation (the number of occupants, the occupancy scenario and paterns, the calculation set point temperature for the heating needs and for the cooling requirements, windows opening hours).

### 3.3 Evaluation criteria

The thermal renovation solutions should be evaluated on a multiple criteria basis. The definition of the evaluation criteria would be accomplished by the Delphi method, which is a structured group interaction method that works through multiple rounds of opinion collections and anonymous feedback. It is a useful tool to obtain a consensus of opinions from a group about an issue not subject to objective solution. Keeney et al. [51] have provided excellent review of the Delphi method and its applications. First using interviews, individual lists of criteria are obtained; each decision maker is asked individually to express their evaluation criteria, taking into accounts different aspects such as: economic, environmental, cultural, and architectural. The criteria can be for example: investment cost, energy consumption decrease, and so on. Secondly, all the individual lists will be combined to form a complete list, which is shared with all decision-makers. They are invited to review this information and to revise and resubmit their initial individual list. This process is repeated until the participants decide that they cannot reduce further the number of criteria in the list. Tavana et al. [44] have already combined Delphi method with PROMETHEE methods. The association of the Delphi method with PROMETHEE method allows improving the communication among the decision makers. It also facilitates the process of the definition of evaluation criteria and the thermal renovation solutions.

### 3.4 Alternative generations:

Once the investigation on the building is completed and the evaluation criteria are defined, the group decision should formulate thermal renovation alternatives. The thermal renovation solutions will take into account only the common area, and will concern only the insulation of the building envelope (external roof insulation, external wall insulation, and so on). This step can be performed with an open discussion among decision makers or through the same process used for the evaluation criteria selection.

### 3.5 Evaluation of the alternatives in terms of the criteria:

Each alternative should be evaluated in terms of all the criteria. These evaluations can be quantitative (obtained from thermal dynamic simulation tool, accounting calculations etc) or qualitative (expert judgments, interviews, and so on).

### 3.6 Defining criteria weights via Swing method:

According to PROMETHEE theory, each decision maker should provide information between the different criteria expressed by weights ($w_j$).They represent the importance of each criterion for the decision maker. However, PROMETHEE methods do not provide any specific technique to define the weights of the criteria. In the literature, the Analytical Hierarchy Process (AHP) method was often combined with PROMETHEE method to help the decision makers to assign weights to the criteria [52]. However, AHP method requires importance ratio judgments between each pair of criteria and the complexity of this method makes it implementation quite inconvenient. In this paper, the Swing method has been used to determine the weights of the criteria. The Swing method uses a reference state in which all criteria are at their worst level, and asks the interviewee to assign points to states in which one criteria at a time moves to the best state. The weights are then proportional to these points. The advantages of the Swing method are that it is fairly fast and interviewees readily give answers. It only requires knowing the criteria ranges. On the other hand, the disadvantages are that the technique is based on direct rating, it does not include consistency checks, and the extreme outcomes to be compared may not correspond to a realistic alternative [53]. Combining Swing method with PROMETHEE methods allow simplifying the determination of the criteria weights. So far, the association of these two methods has not been performed in multi criteria decision literature.

### 3.7 Individual ranking PROMETHE II

In this step, each decision maker should provide information within the same criterion expressed by preference functions ($P_j(a,b)$). They represent for each pair of alternatives "*a*", "*b*" the preference intensity of "*a*" over "*b*". A multi-criteria preference index is defined as in equation (1).

$$\pi(a,b) = \sum_{j=1}^{k} w_j \times P_j\,(a,b) \qquad (1)$$

Where $\pi\,(a, b)$, expresses the preference degree of "*a*" over "*b*" regarding all the criteria, it varies from 0 to 1.

Where $w_j$, is the normalized weight assigned to criterion *j*

The facilitator would help the decision-makers to choose their preference functions. There are six different types of criterion according to their preference functions [54]. In addition, decision makers should specify the threshold values p (strict preference threshold when the difference between two actions "*a*" and "*b*" is very strong and very important to the decision maker) and q (indifference threshold when the difference between the actions "*a*" and "*b*" is insignificant).

The weights and the preference functions of the decision makers will be used to compare the actions. First, the leaving flow and the entering flow have to be calculated:

The leaving flow *Phi*+ *(Ø+)* represents a strength measure. It is a number between 0 and 1; this means that for a given action, if the leaving flow is 1, the action is preferable to all the others actions on all the criteria, and if the leaving flow is equal to 0, this means that the action does not represent any advantage over the other actions. *Phi*+ is calculated with equation (2).

$$\emptyset^{+}(a) = \frac{1}{n-1} \sum_{b \neq a} \pi\,(a, b) \qquad (2)$$

The entering flow *Phi*- *(Ø⁻)* represents a weakness measure. It is a number between 0 and 1, where 0 is the best solution and 1 the worst one. *Phi*- is calculated with equation (3).

$$\emptyset^{-}(a) = \frac{1}{n-1} \sum_{b \neq a} \pi\,(a, b) \qquad (3)$$

Secondly, we calculate the net flow *Phi (Ø)*. It represents the difference between the two flows as shown in equation (4). The net flow allows establishing a comprehensive ranking of actions. Then the decision problem could be illustrated through the GAIA analysis (Graphical Analysis for Interactive Aid). It allows a better understanding of conflicts and similarities between the criteria and the performance of each action regarding different criteria.

$$\emptyset(a) = \emptyset^{+}(a) - \emptyset^{-}(a) \qquad (4)$$

Additional constraints can be introduced according to the requirements of the decision makers through PROMETHEE V. A binary variable (0-1) $x_i$ is associated with each action "$a_i$": $x_i = 1$ means that the action "$a_i$" is selected, $x_i = 0$ means it is not. The aim is to select the actions so that the sum of the Phi (Ø) of these actions is maximum as shown in equation (5).

$$max \sum_{i=1}^{n} \emptyset\ (a_i)x_i \qquad (5)$$

### 3.8 Global ranking: GDSS PROMETHEE

The global net flow of the group decision can be obtained directly by the weighted sum of the individual flows equation (6). The global flow for a given alternative is express as follows:

$$\emptyset_g(a) = \sum_{s=1}^{S} w_s\ \ \emptyset^{s}(a) \qquad (6)$$

Where $w_s$ is the normalized weight assigned to each DMs

The global net flows provide directly the PROMETHEE GDSS ranking of the alternatives following the group decision preferences. Additional constraints can be added through PROMETHEE V as well. Later the global GAIA analysis is used for the global ranking. It contributes to understand the preferences of the different decision makers.

### 3.9 Sensitivity analysis

First, the effect of changing the criteria weights on the rank of the thermal renovation solutions for each decision maker should be analysed. Secondly, the effect of changing the weights of the decision makers on the global ranking should be studied as well.

## 4 Case study :

In this section, a case study is presented. It is the building number 11 Boulevard Matta, Oran, Algeria. It is a neoclassical colonial collective building, constructed in masonry between the late 19th century and early 20th century (see Figure 2). The aim of this case study was to test the applicability of the method in the thermal renovation of masonry buildings.

Figure 2: Neoclassical colonial collective building constructed in masonry

### 4.1 Decision context definition

Fours (DM) participated in this study. Although, the group members were not selected by ourselves. We contacted by phone and emails the stakeholders concerned about the thermal renovation. Following this, each stakeholder appointed a representative to express their interests and point of views. DM1 was a representative of the national agency for the promotion and the rationalization of the energy use (APRUE), an agency in charge of the energy consumption reduction in the residential sector in Algeria. DM 2 represented the department of urban planning and construction (DUC), a national department in charge of masonry buildings' preservation in Algeria. DM3 was the representative of all the building's users selected by themselves. DM4 was an expert from a private expert firm in the thermal renovation of masonry buildings, which has been selected by the government to undertake the refurbishment of these specific buildings.

## 4.2 Case study investigation

The group decision makers have conducted a pre-evaluation of the building design plans and documentation as well as the level 1 audit (Walk-through assessment) as indicated in subsection 3.2. The total building volume is 2,320 m3. The floor- area is 580 m2. The building has four flats occupied by four different family. Concerning the scenario occupation, there is at least one person occupying each flat for almost all the times. The annual energy consumption for heating and cooling of the building is about 66,332 kWh. The building is equipped with a collective heating system and four individual air conditioning systems. The building does not have any mechanic ventilation and is ventilated naturally. The set point temperature for the heating system is 21 ° C, and 26 ° C for the cooling systems. The Exterior masonry walls have a thickness of 55 cm and a U-value of 1.19 W/m2K. The roof is built in vaulted brick floor and metal beams; it has a U-value of 1.69 W/m2K. The windows are all single glazed with a U value 5.68 W/m2K. The roof, walls, and widows are not damaged. However, they are not insulated which consequently make the building consumes more energy. The main façade is well conserved. It presents historic aesthetic features while the secondary and courtyard facades as well as the roof does not present such features

## 4.3 Evaluation criteria

The Delphi technique is used to gather input from those 4 DM without requiring them to work face to face. We used semi structured interview to gather information, obtain feedback and make conclusions. In the first Delphi round, the DMs were asked individually to consider the economic, energetic, environmental, architectural, social, and technological issues and to compile and explain a set of criteria considered to be important in the thermal renovation project. These personal lists were provided to the facilitators anonymously. Then, the facilitators combined all of these criteria into a list of 11 criteria as indicated in table 1. In round 2, this list was shared with all the DMs. They are invited to review this information, to revise, and resubmit their initial individual list. The facilitators combined all of these criteria into a new list of 7 criteria as shown in table 1. Again, in round 3, the synthesized list of criteria from round 2 was shared with all the DMs, and they were asked to revise and resubmit their individual list from round 2. The facilitators then combined all of these criteria into another new list with 4 criteria. At this point, the DMs agreed that they could not reduce further the number of criteria in the list. Consequently, a decision was made to use the 4 evaluation criteria (the energy consumption, the investment cost, the risk of the loss of building historic aesthetic features and the risk of the fabric) obtained from round 3 as presented in table 1.

| Rounds | Criteria code | Classification | Criteria |
|---|---|---|---|
| Round 1 | 1 | Economic | Investment cost |
| | 2 | Economic | Payback period |
| | 3 | Technological | Availability of Manpower |
| | 4 | Technological | Availability of materials |
| | 5 | Energetic | Energy consumption decrease |
| | 6 | Environmental | Decrease of CO2 emissions |
| | 7 | Architectural | Risk of the fabric decay |
| | 8 | Architectural | Risk of the loss of building historic aesthetic features |
| | 9 | Social | Summer comfort |
| | 10 | Social | Inconvenience caused by the thermal renovation |
| | 11 | Social | Duration of the thermal renovation work |
| Round 2 | 1 | Economic | Investment cost |
| | 2 | Economic | Payback period |
| | 5 | Energetic | Energy consumption decrease |
| | 6 | Environmental | Decrease of CO2 emissions |
| | 7 | Architectural | Risk of the fabric decay |
| | 8 | Architectural | Risk of the loss of building historic aesthetic features |
| | 9 | Social | Duration of renovation work |
| Round 3 | 1 | Economic | Investment cost |
| | 5 | Energetic | Energy consumption decrease |
| | 7 | Architectural | Risk of the fabric decay |
| | 8 | Architectural | Risk of the loss of building historic aesthetic features |

Table 1: Selection of evaluation criteria through Delphi method

The evaluation indicators were chosen in such way that they could be easily understood by the group decision. The energy consumption was expressed with the heating and air conditioning annual need decrease. This evaluation was done under TRANSYS [55], which is a dynamic thermal simulation software. The investment cost was expressed in Algerian dinars (converted in this paper to US dollar). It included the supply costs and the labour. The risk of the loss of building historic aesthetic features was evaluated by means of subjective judgments and expressed in qualitative scale (see Table 2). The risk of the fabric decay in the walls is due to moisture accumulation, which might happen when additional thermal renovation solutions are not adapted to the masonry building [10]. In this research all thermal renovation alternatives were evaluated in terms of moisture accumulation under the WUFI (Wärme Und Feuchte Instationär—which, translated, means heat and moisture transiency) software [56], WUFI allows the simulation of heat and mass transfer in walls [57]. According to the result, the risk of fabric decay of each solution was expressed by qualitative scale (see Table 2).

| Scale | Risk level |
|---|---|
| 1 | Very low |
| 2 | Low |
| 3 | Medium |
| 4 | High |
| 5 | Very high |

Table 2: Qualitative scale for risks evaluation

**4.4 Alternative evaluation:**

Still using the Delphi method, DM1, DM2 and DM4 generated thermal renovation alternatives. The thermal renovation solutions took into account only the common area, and concerned only the insulation of the building envelope (see Table 3).

### 4.5 Evaluation of the alternatives in terms of the criteria

Table 3 shows the evaluation of all the alternatives in term of the selected criteria.

| Codes | Actions (thermal renovation solutions) | C1<br><br>KWh | C2<br><br>US dollar | C3<br><br>Qualitative | C4<br><br>Qualitative |
|---|---|---|---|---|---|
| A1 | Exterior insulation of the main facade with 10 cm of expanded polystyrene | 6675 | 1611 | Very high | Very high |
| A2 | Exterior insulation of the main facade with 10 cm of cellular concrete | 6296 | 2255 | Very high | Low |
| A3 | Exterior insulation of the main facade with 10 cm of wood fiber | 6384 | 1772 | Very high | Low |
| A4 | Exterior insulation of the main facade with 6 cm of lime hemp plaster | 4062 | 1933 | Very low | Very low |
| A5 | Exterior insulation of the secondary facade and courtyard with 10 cm of expanded polystyrene | 5461 | 1295 | Medium | Very high |
| A6 | Exterior insulation of the secondary facade and courtyard with 10 cm of cellular concrete | 5155 | 1813 | Medium | Low |
| A7 | Exterior insulation of the secondary facade and courtyard with 10 cm of wood fiber | 5223 | 1424 | Medium | Low |
| A8 | Exterior insulation of the secondary facade and courtyard with 6 cm of lime hemp plaster | 3482 | 1554 | Very Low | Very Low |
| A9 | Exterior insulation of the roof with 10 cm of expanded polystyrene | 8918 | 2669 | Very low | Low |
| A10 | Exterior insulation of the roof with 10 cm of wood fiber | 8623 | 2936 | Very low | Low |
| A11 | Exterior insulation of the roof with 15 cm of expanded polystyrene | 9897 | 4004 | Very low | Low |
| A12 | Exterior insulation of the roof with 15 cm of wood fiber | 9618 | 4271 | Very low | Low |
| A13 | Double glazing window installation. | 12188 | 7330 | Medium | - |
| A14 | Double windows installation | 11027 | 7521 | Very low | - |
| A15 | Secondary glazing installation | 5200 | 2255 | Very low | |

C1: Energy consumption decrease; C2: Investment cost; C3: Risk of the loss of building historic aesthetic features, C4: Risk of the fabric decay

Table 3: Evaluation table

### 4.6 Defining criteria weigh via Swing method

The weights of the criteria were defined through SWING method using a reference state where all criteria were at their lowest level. Each decision maker was asked which criterion he would improve to the highest level, assuming that only one criterion could be improved. The next step consisted in asking the decision maker to give a value to (e.g. in the range 0–100) to this swing in terms of importance. The score 100 represented the maximum importance. Finally, the scores were normalized to sum up to one to get the criteria weights. The weight of DM3 represented the average weight of all building users (see Table 4). DM1 and DM3 considered the criteria investment cost and energy consumption decrease as very important. While the criteria risk of the loss of building historic aesthetic features and the risk of the fabric decay were less important. For DM2, the criteria risk of the loss of building historic aesthetic features and the risk of the fabric decay were respectively very important. Whilst the criteria energy consumption decrease and investment cost were less important. For DM4 the criteria risk of fabric decay, risk of the loss of building historic aesthetic features, energy consumption decreases were respectively important. The investment cost was less important.

| Criteria | | C1 | C2 | C3 | C4 |
|---|---|---|---|---|---|
| DM1 | Weight | 0.279 | 0.264 | 0.220 | 0.235 |
| | Preference | Usual | Usual | Level<br>q=1<br>p=2 | Level<br>q=1<br>p=2 |
| DM2 | Weight | 0.235 | 0.220 | 0.279 | 0.264 |
| | Preference function | Usual | Usual | Usual | Usual |
| DM3 | Weight | 0.275 | 0.284 | 0.226 | 0.213 |
| | Preference function | Usual | Usual | Level<br>q=1<br>p=2 | Level<br>q=1<br>p=2 |
| DM4 | Weight | 0.262 | 0.205 | 0.264 | 0.269 |

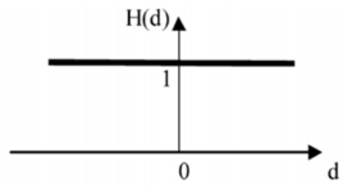
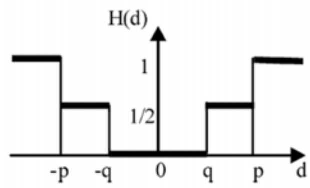
| | | | | | |
|---|---|---|---|---|---|
| | Preference function | Usual | Usual | Level q=1 p=2 | Level q=1 p=2 |

C1: Energy consumption decrease; C2: Investment cost; C3: Risk of the loss of building historic aesthetic features, C4: Risk of the fabric decay, q represents the indifference threshold and p represents the preference threshold.

Table 4: Weights, preference functions, threshold parameters evaluated per decision-makers

### 4.7 Individual ranking PROMETHE II and analysis

According to PROMETHEE theory, each decision maker has provided information within the same criterion expressed by preference functions (Pj(a,b)). The preference functions type I, and types IV (see Table 4 and Table 5) were chosen by the decision makers.

| Generalized criterion type | Preference functions (*H*(*d*)), *d* = *gj(a)*−*gj(b)* | |
|---|---|---|
| Type I: Usual criterion. $H(d) = \begin{cases} 0 \; if \; d = 0 \\ 1 \; if \; d \neq 0 \end{cases}$ | None |   |
| Type IV: Level criterion (best suited for qualitative criteria) $H(d) = \begin{cases} 0 \; if \; \lvert d \rvert \leq q \\ \frac{1}{2} if \; q < \lvert d \rvert \leq p \\ 1 \; if \; p < \lvert d \rvert \end{cases}$ | *q,p* |   |

*gj(a)* is the performance of alternative "*a*" in criterion "*j*". "*q*" represents the indifference threshold and "*p*" represents the preference threshold.

Table 5: The shapes of the two preference functions used in this paper adapted from Vincke and Mareschal [54]

Under Visual PROMETHEE software [58] it was possible to get an individual ranking PROMETHE II for each decision maker (see Table 6). For this purpose, three additional constraints (number of actions to select, incompatibilities between actions, maximum budget available) were added since there were 15 alternatives and only 4 could have been selected simultaneously, the maximum budget available was about 16.000 US dollar. These constraints were taken into account through PROMETHEE V method.

The constraint of the number of actions to select is indicated in equation (7).

$$\sum_{i=1}^{n} x_i = 4 \qquad (7)$$

Where 4, represents the number of actions to select, and $x_i$ is a binary variable (0-1) associated to each action $a_i$: $x_i$= 1 means that action $a_i$ is selected while $x_i$ = 0 means it is not.

The constraints of the incompatibilities between actions (A) are indicated in equation (8, 9, 10, and 11).

$$A1 + A2 + A3 + A4 = 1 \qquad (8)$$

$$A5 + A6 + A7 + A8 = 1 \qquad (9)$$

$$A9 + A10 + A11 + A12 = 1 \qquad (10)$$

$$A13 + A14 + A15 = 1 \qquad (11)$$

The constraint of the maximum budget available is expressed in equation 12

$$\sum_{i=1}^{n} b_i \times x_i \leq 16.000 \qquad (12)$$

Where the number 16.000 represents the maximum budget available (in US dollar), and $b_i$ corresponds to the investment cost of each action $a_i$.

| Ranking | DM1 | DM2 | DM3 | DM4 |
|---|---|---|---|---|
| 1 | A7 | A8 | A7 | A7 |
| 2 | A11 | A11 | A9 | A11 |
| 3 | A13 | A4 | A13 | A13 |
| 4 | A3 | A14 | A3 | A4 |

Table 6: Individual PROMETHEE II ranking with additional constraints

Table 6 shows that the ranking of the thermal renovation solutions was different for all decision makers. DM1 and DM3 provided almost a similar ranking. The only difference is that for DM3 A9 is preferable to A11. A3 was selected by both of DM1 and DM3, this action represents very high risk of loss of building historic aesthetic features, which shows that DM1 and DM3 do not give enough importance to this criterion. DM4 provided a ranking close to DM1 with A7, A11, and A13 in the top row. The difference is that A4 is preferred to A3. DM4 has almost succeeded to balance between all the criteria. DM2 had a completely different ranking from the previous decision makers. A8, A4, and A14 had very weak performance on the energy consumption decrease and the investment cost, which shows that DM2 does not give enough importance to those two criteria. He cares only about the risk of fabric decay and the risk of the loss of building historic aesthetic features.

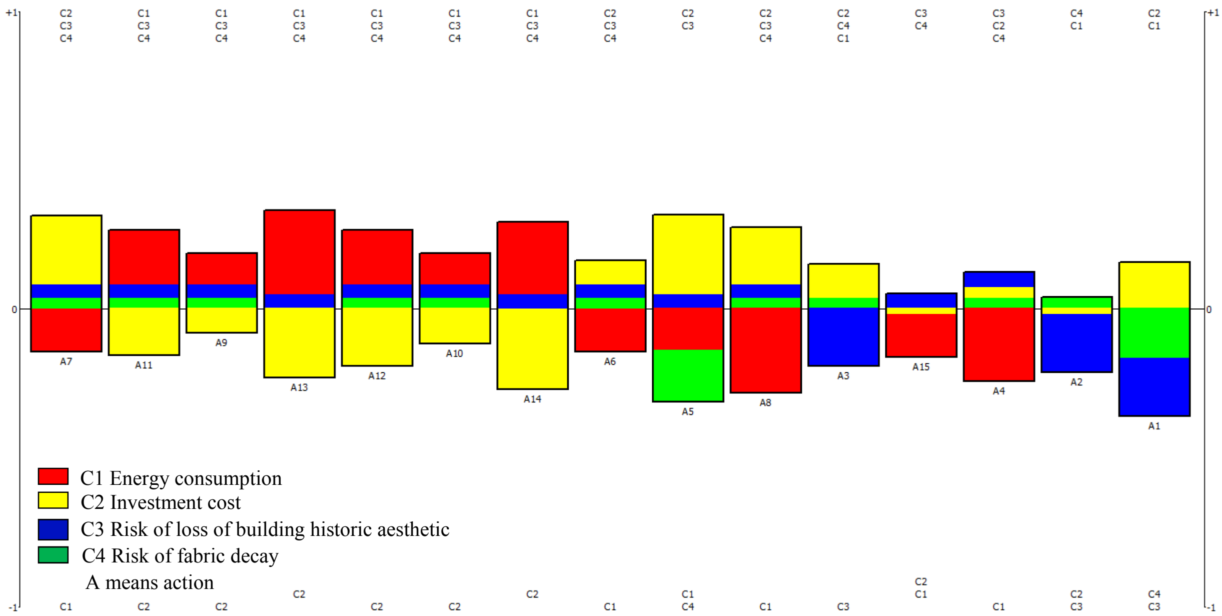


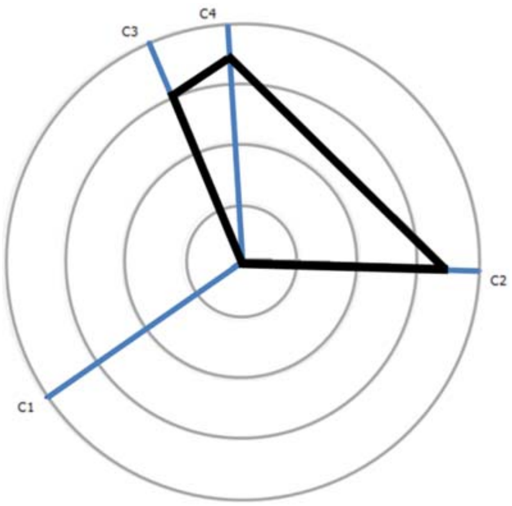

Figure 3: Details of the phi net flow computation for DM1

For example Figure 3 shows the detail of the Phi net flow computation for DM1, highlighting the good and weak characteristics of each action. For each action, a bar was drawn. The different parts of each bar were coloured according to the colour coding of the criteria. Each part is equivalent to the influence of one criterion to the phi net flow score of the action. Positive (upward) parts correspond to good characteristics, while negative (downward) parts correspond to weaknesses. The balance between positive and negative slices is equal to the phi score. Actions were ranked from left to right according to the PROMETHEE II Complete Ranking (without the additional constraints).

For DM1, the actions A7, A11, A13, and A3 were preferable to all the other actions (see Table 5) .The exterior insulation of the secondary facade and courtyard with 10 cm of wood fiber (A7) had very good features in the investment cost (C2), good features in the risk of the loss of building historic aesthetic features (C3) and the risk of fabric decay (C4), however it had weak features in the energy consumption decrease (C1). The exterior insulation of the roof with 15 cm of expanded polystyrene (A11) and the double glazing window installation (A13) both had very good features in the energy consumption (C1). They had good features in the risk of the loss of building historic aesthetic features (C3). They had very week features in the investment cost (C2). The exterior insulation of the main facade with 10 cm of wood fiber (A3) had very good features in the investment cost (C2). It had medium features in the energy consumption decrease (C1). It had low risk of fabric decay (C4). It had very week features in the risk of the loss of building historic aesthetic features (C3).

Based on the above ranking of DM1, (A7) was the best action despite the fact that it has weak features in the most important criteria for DM1 (energy consumption decrease). This implies that the best thermal renovation solutions are not those that have the best performance in the criteria with the highest weight, but they are those that represent the best compromise.

Then the GAIA Web was drawn to illustrate conflicts and similarities between the criteria for each decision maker. Furthermore, it allows understanding the performance of each action concerning the different criteria. The GAIA Web shows a graphical representation of the unicriterion net flow scores for a selected action. The criteria vectors (blue colour) which express the same preferences have similar orientation while conflicting criteria have opposite direction. For each criterion, the radial distance corresponds to the net flow score (-1 at the center and +1 on the outer circle). For example, Figure 4 shows the GAIA web for DM2 when action A8 is selected. The exterior insulation of the secondary facade and courtyard with 6 cm of lime hemp plaster (A8) had very good features in the investment cost, in the risk of the loss of building historic aesthetic features and in the risk of fabric decay. However, it had very weak features in the energy consumption decrease. The criteria risk of the loss of building historic aesthetic features and risk of fabric decay almost share the same orientation and express similar preferences. The criteria investment cost and energy consumption decrease have opposite orientation and express conflicting preferences.




C1: Energy consumption decrease; C2: Investment cost; C3: Risk of the loss of building historic aesthetic features, C4: Risk of the fabric decay

Figure 4: GAIA web for DM2 when action A8 is selected

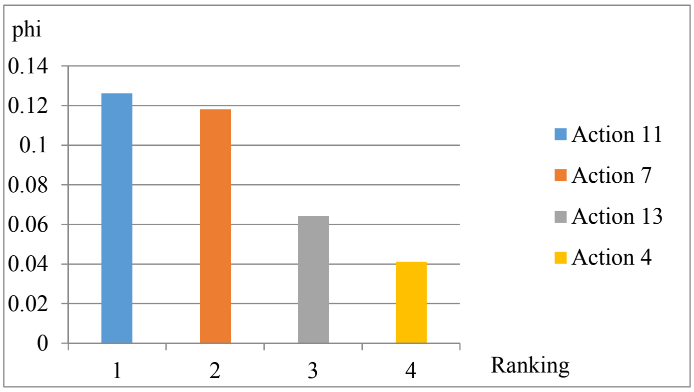
**4.8 Global ranking PROMETHEE GDSS and analysis**

The net flow of the 4 decision makers (DM) were collected together in a global decision matrix as indicated on Table 7.

| Action | DM1 Net flow | DM2 Net flow | DM3 Net flow | DM4 Net flow |
|---|---|---|---|---|
| A1 | -0.205 | -0.302 | -0.183 | -0.308 |
| A2 | -0.174 | -0.255 | -0.183 | -0.201 |
| A3 | -0.042 | -0.145 | -0.041 | -0.098 |
| A4 | -0.12 | 0.158 | -0.116 | -0.088 |
| A5 | 0.004 | -0.185 | 0.043 | -0.062 |
| A6 | 0.016 | -0.154 | 0.022 | 0.03 |
| A7 | 0.168 | -0.028 | 0.185 | 0.148 |
| A8 | -0.009 | 0.251 | 0.007 | -0.006 |
| A9 | 0.105 | 0.16 | 0.095 | 0.127 |
| A10 | 0.067 | 0.129 | 0.055 | 0.097 |
| A11 | 0.109 | 0.164 | 0.093 | 0.139 |
| A12 | 0.071 | 0.133 | 0.052 | 0.11 |
| A13 | 0.099 | -0.053 | 0.079 | 0.13 |
| A14 | 0.022 | 0.12 | 0 | 0.065 |
| A15 | -0.111 | 0.006 | -0.109 | -0.083 |

Table 7: Global decision matrix

A PROMETHEE GDSS global ranking was performed. The same constraints used in the individual ranking were introduced through PROMETHEE V. According to Macharis et al. [43], all the decision-makers had the same relative importance (the same weights, DM1 0.25, DM2 0.25, DM3 0.25, DM4 0.25). From the group decision viewpoint, the actions A11, A7, A13 and A4 are respectively preferable to all the other actions (see Figure 5).




Where phi is the global net flow of the group decision for each action.

Figure 5: Global ranking PROMETHEE GDSS under constraints

The decision problem was then represented using the GAIA plan (see Figure 6), it provides help to understand the different decision makers' preferences and the performance of each action for them. The GAIA plan is the result of principal component analysis, and it preserves the highest possible amount of information after the projection. The projection of 4 dimensional spaces of the criteria in a two dimensional plane preserved 97.4% the total data. The Information provided in this paper by the GAIA plan is considered reliable since their value is greater than 80% as explained by Figueira, J et al. [59]. The length of decision axis (red axis) is a force measure for the differentiation between two alternatives. The alternatives are presented by dots. The actions with the same colour cannot be selected simultaneously. The decision makers are represented by vectors. The decision makers who share the same preferences have similar orientation while those with conflicting preferences have different directions.

The actions A11, A9, A7, A12, A10, and A13 are the closest from the direction of the decision axis so they represent the best alternatives. The actions A8, A14, A6, and A4 are less preferable and more distant from the direction of the decision axis. The actions A5, A15, A3, A2, and A1 are the least preferable and the furthest from the direction of the decision axis. The vectors of DM1 and DM3 share the same orientation so they have similar preferences. The vector of DM4 has almost the same direction of DM1 and DM3. However, the vector of DM2 has a completely different direction from the others. Consequently, DM2 has very different preferences compare to DM1, DM3, and DM4. This clarifies why DM1, DM3, and DM4 had less or more a similar individual ranking while DM2 had a completely different individual ranking.

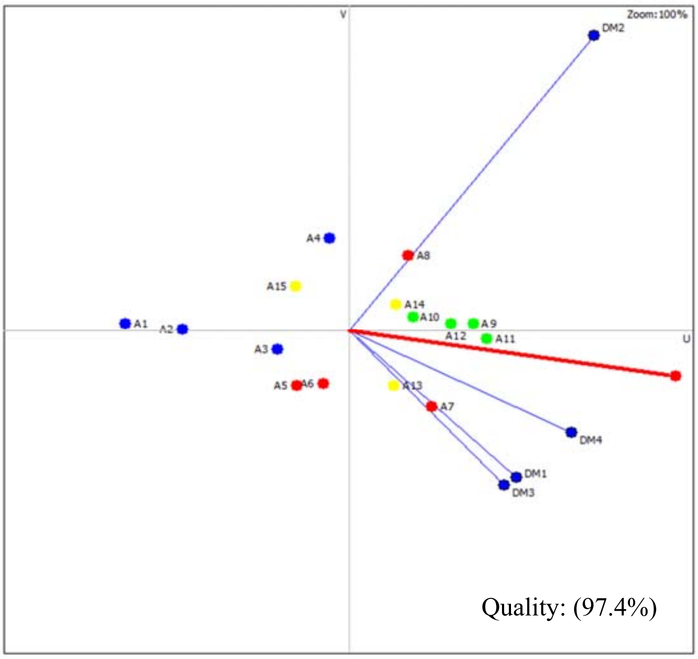



Figure 6: Global GAIA plane

### 4.9 Sensitivity Analysis

PROMETHEE method involves the determination of subjective parameters (criteria weights, decision maker's weights) [27]. It is interesting to investigate the influence they have on the rankings when deviations in their values are introduced. First, an analysis was done about how changing the weights assigned to the criteria could affect the rank of the selected thermal renovation solutions for each decision maker. This analysis was performed through the investigation of the weight stability intervals under visual PROMETHEE software [58]. The weight stability intervals give the limits for each criterion where variations of the criterion weight in term of percentage would not alter the individual PROMETHEE ranking of the thermal renovation solutions.

Table 8 shows the weight stability intervals in percentage terms of all the criteria for each decision maker (DM). Hence, changing the weight of energy consumption decrease within the interval [27%, 30%] would not affect the rank of the selected alternatives for DM1. Similarly, modifying the weights of the risk of the loss of building historic aesthetic features between 10 and 99 % will not change the rankings for DM2. It can be noted that the information provided by the stability intervals applies only when the weights are modified singly.

| Criteria | DM1 | | DM2 | | DM3 | | DM4 | |
|---|---|---|---|---|---|---|---|---|
| | % weight stability intervals | | % weight stability intervals | | % weight stability intervals | | % weight stability intervals | |
| | Min | Max | Min | Max | Min | Max | Min | Max |
| C1 | 27 | 30 | 22 | 27 | 21 | 28 | 22 | 26 |
| C2 | 24 | 28 | 20 | 22 | 28 | 34 | 21 | 23 |
| C3 | 10 | 29 | 10 | 99 | 13 | 27 | 26 | 99 |
| C4 | 19 | 62 | 23 | 27 | 12 | 57 | 23 | 71 |

Table 8: Weight stability intervals of the criteria

Secondly, the stability of the ranking of the selected solutions from the group decision view point was analysed by a final sensitivity analysis (see Table 9). In this analysis, the weight stability intervals give the limits for each decision maker where variations of the decision maker's weights in term of percentage would not alter the group decision ranking PORMETHEE GDSS of the thermal renovation solutions. The final sensitivity analysis reveals that changing the weight from [12%, 50%] for DM1, [12 %, 51%] for DM3, [22 %, 49%] in DM2, and [8 %, 62%] for DM4 would not affect the global ranking of the thermal renovation solutions, which is a large range of variation. The sensitivity analysis revealed that considerable changes in decision maker's weights would not affect the global ranking; this proves that the proposed method is robust with respect to the different decision maker's preferences.

| Decision maker | % Weight of decision maker | % Weight stability intervals | |
|---|---|---|---|
| | | Min | Max |
| DM1 | 25 | 12 | 50 |
| DM2 | 25 | 22 | 49 |
| DM3 | 25 | 12 | 51 |
| DM4 | 25 | 8 | 62 |

Table 9 Weight stability intervals of the DMs

## 5 Evaluation of the method

The proposed method considers each thermal renovation of masonry building project as a unique, with its own context, actors, specificity and patrimonial value. The method does not aim to define standard evaluation criteria or thermal renovation solutions as proposed in [8-10], but it offers a logical approach to determinate the most relevant criteria according to a specific context and to rank the best thermal renovation solutions.

The MCDA approaches used for the thermal renovation considered only the preferences of building users by either interviews [20] or questionnaires methods [21]. However, the proposed method takes the preferences of several stakeholders into account (actor concerned with the preservation of buildings, actor concerned by the reduction of energy consumption, building users, expert). It uses the Delphi method to improve the communication among the decision makers and help them to obtain a consensus regarding the definition of evaluation criteria and thermal renovation solutions. The selected criteria in this paper were considered as relevant as they satisfied the general requirements listed by Keeney et al. [51].

Concerning the weight elicitation, the Swing method was effective to simplify the process of the determination of the criteria weights. The interview questions were clearly presented as confirmed by the respondents, which agrees with Ferretti et al. [60]. However, according to the case study in this paper, the Swing method seems to be not suitable when a respondent expresses uncertainties and vagueness in judgments. To the best of our knowledge, the paper extends the literature in multi-criteria decision analysis as the Swing method has not been combined with the PROMETHEE methods before.

Most of the MCDA applied in the thermal renovation literature uses the complete aggregation approach or the partial aggregation methods ELECTRE. So far, the partial aggregation method PROMETHEE GDSS group decision has not been used in this area. The main contribution of the proposed method is to use PROMETHEE GDSS. The method takes into account the preferences of different decision makers in order to get a global ranking of the thermal renovation solutions. Furthermore, it allows taking into account several quantitative and qualitative criteria without having to do any coding contrary to the other methods reviewed in the literature [9, 10, 17-21] where it is necessary to carry out coding. In addition, the proposed method does not allow the compensation between criteria. Indeed, the result shows that the best thermal renovation solutions are not those that have the best performance in the criteria with the highest weight but those which represent the best consensus, this agrees with Macharis et al. [27].

The method offers the possibility to introduce additional constraint through PROMETHEE V. This feature is very useful for real life problems when the number of actions or the available budget is limited according to Brans [40]. The method provides completely innovative features in the thermal renovation literature; it uses the GAIA analysis for a better understanding of the conflicts and similarities between the criteria and among decision makers. Furthermore, it helps to solve conflicts between decision makers as indicated by Macharis et al. [43].

The method has been implemented with a real team and real data for a planned project. It has been validated by the decisions makers. Although, a debate among the decision makers took place to finalise and digest the outcome of the proposed method. They all considered the selected criteria as relevant. Furthermore, the global ranking was accepted by all the decision makers, they all agreed that the selected thermal renovation solutions represent the best consensus to balance between all the criteria. In addition, the results have also been validated through a sensitivity analysis. It has been checked that the solutions found were stable and were not influenced by the decision-maker preferences. However, it should be noticed that the thermal renovation solutions were not implemented yet. The method described in this article is universal, and can always be applied for selecting thermal renovation solutions when masonry buildings are considered.

## 6 Conclusions

The paper has an innovative value due to the proposal of a new group decision aid method in both multi-criteria decision and thermal renovation of masonry buildings literature. The proposed method combines the Delphi method, the Swing method, and the PROMETHEE methods. The aim of the proposed method is to rank different thermal renovation solutions using multi-criteria and multi-decision makers approach. A case study was presented to test the applicability of the method in the thermal renovation of masonry buildings. The results showed that it was possible to get a full ranking of the renovation solutions. The Delphi method was effective to select the relevant criteria and the potential thermal renovation solutions. From the group decision viewpoint, the relevant criteria were the energy consumption decrease, the investment cost, the risk of the loss of building historic aesthetic features, and the risk of fabric decay. The Swing method simplified the pro-cess of the determination of the criteria weights. The PROMETHEE methods provided the best consensus between the decision makers. The best solutions were respectively the exterior insulation of the roof with 15 cm of expanded polystyrene, the exterior insulation of the secondary facade and courtyard with 10 cm of wood fiber, and the double-glazing window installation and the exterior insulation of the main facade with 6 cm of lime hemp plaster. The sensitivity analysis reveals that the proposed method is robust with respect to the different decision maker's preferences. However, there are several limitations to the proposed methodology. The method requires working on a set of effective thermal renovation solutions determined by the group decision in the alternative generation step. In subsequent work, the use of multi-objective optimization method in this step can be studied. It will help decision makers to reduce the research area, only the relevant solutions regarding the specificity of the existing building would be taken into account. Furthermore, different uncertainties that can affect the final ranking were not taken into account by the method. For future research, it would be relevant to consider uncertainties concerning the evaluation of the criteria and uncertainties regarding the decision-makers preferences.

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